Metal Additive Manufacturing Process Selection and Development for Propulsion Components

Paul Gradl, Alison Park, Darren Tinker
National Aeronautics and Space Administration (NASA)

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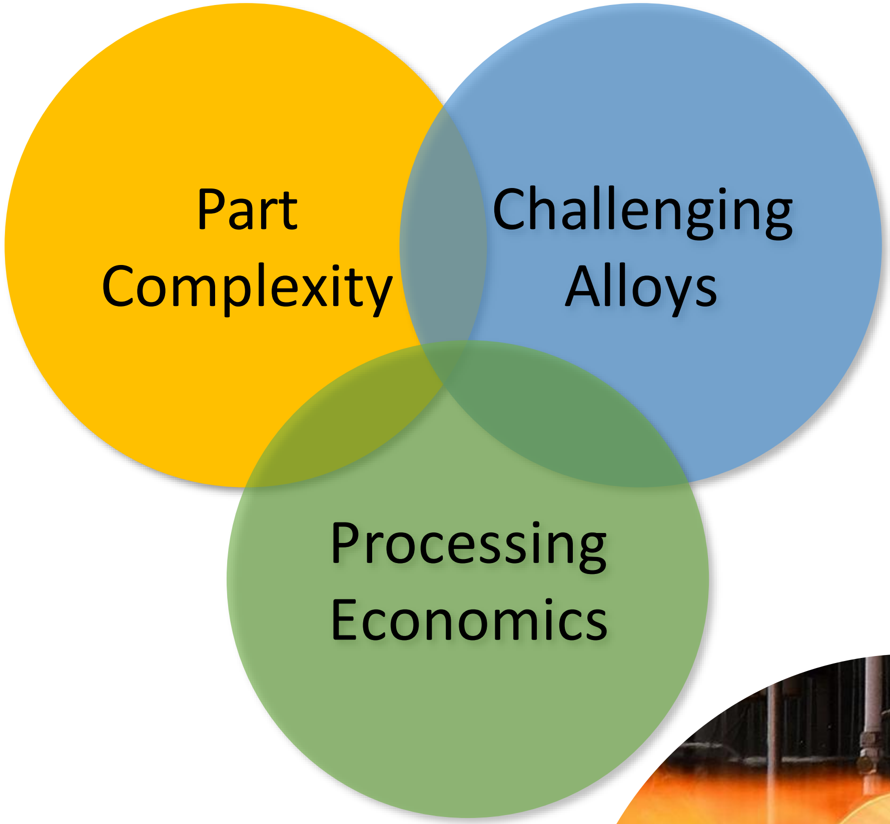
The Case for Additive Manufacturing in Propulsion

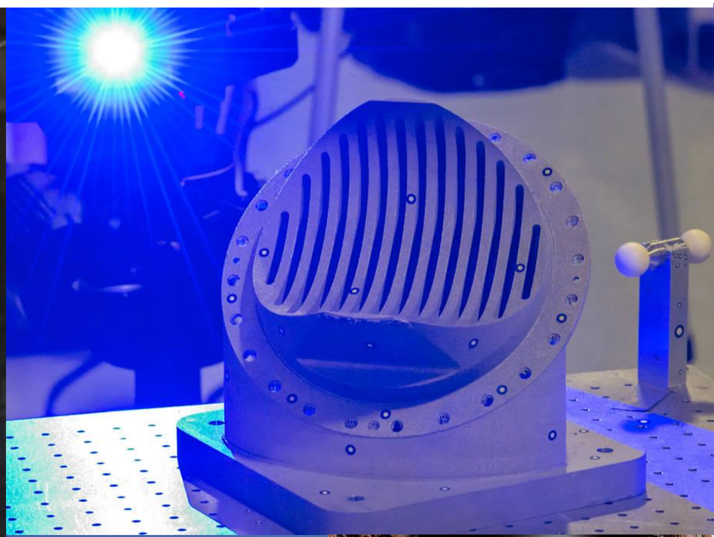
- Metal Additive Manufacturing (AM) can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%

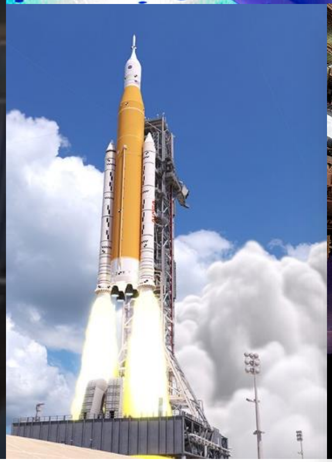
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities.

- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing.



Additive Manufacturing in use on NASA Space Launch System (SLS)

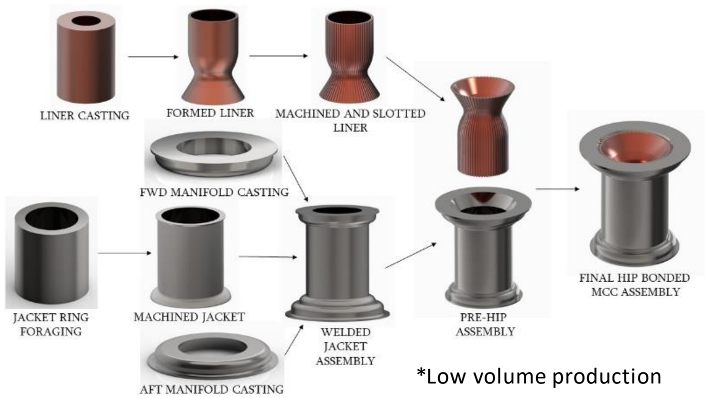




Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

Ref: Andy Hardin, Steve Wofford/ NASA MSFC

A rocket combustion chamber case study for AM

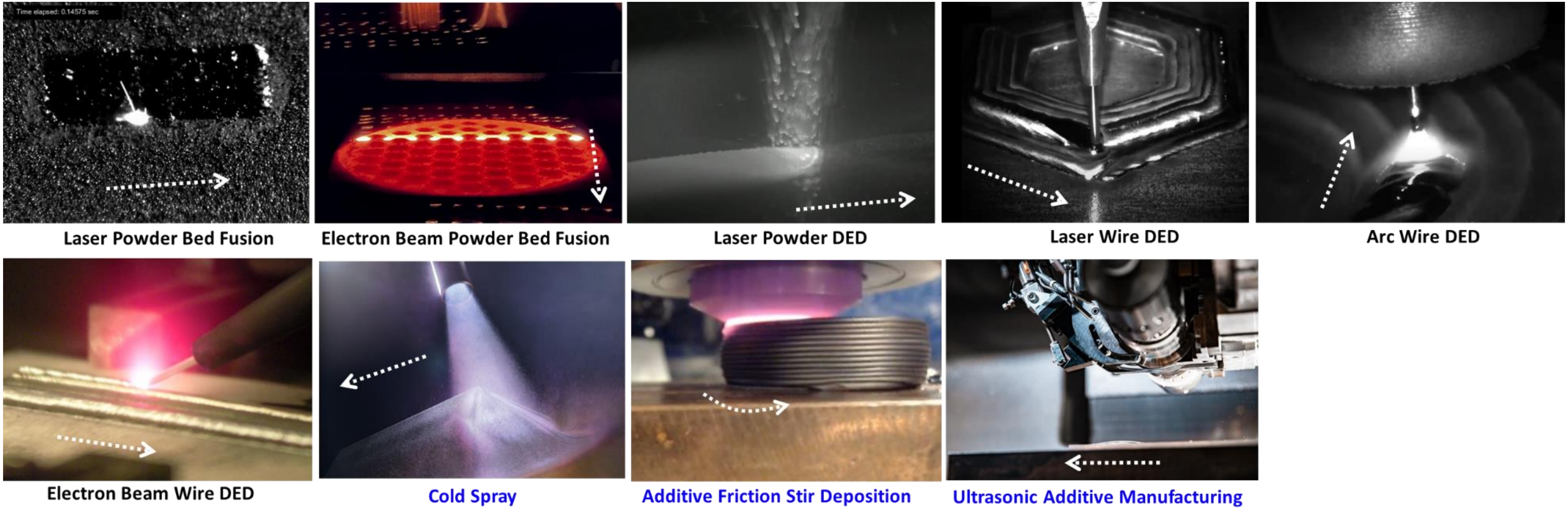


*Low volume production

Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

AM Processes for various applications



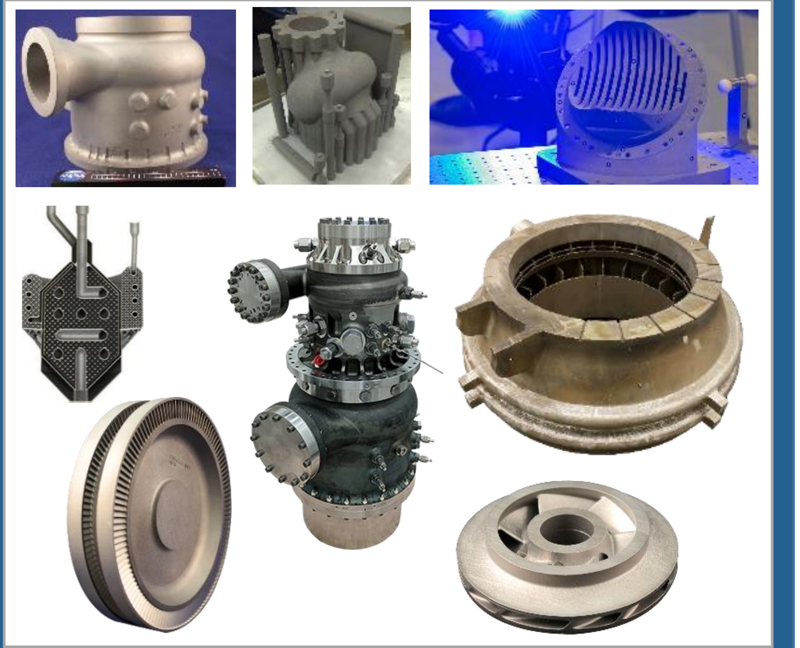
A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden],* C) Laser Powder DED *[Credit: Formalloy],* D) Laser Wire DED *[Credit: Ramlab and Cavitar],* E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar],* F) Electron Beam DED *[NASA],* G) Cold spray *[Credit: LLNL],* H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic].*

Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.

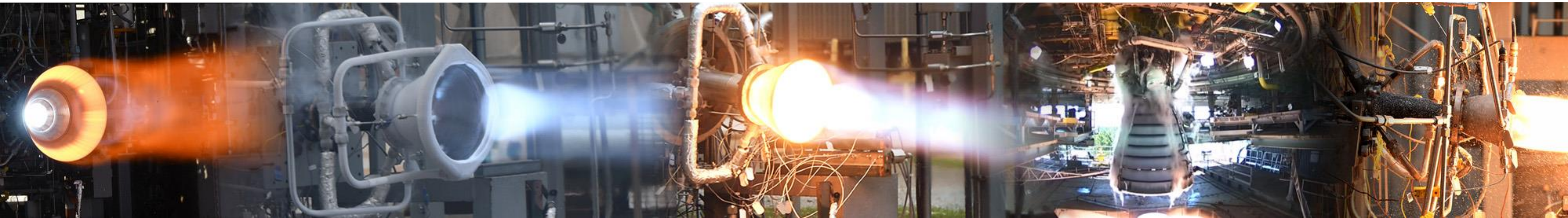
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

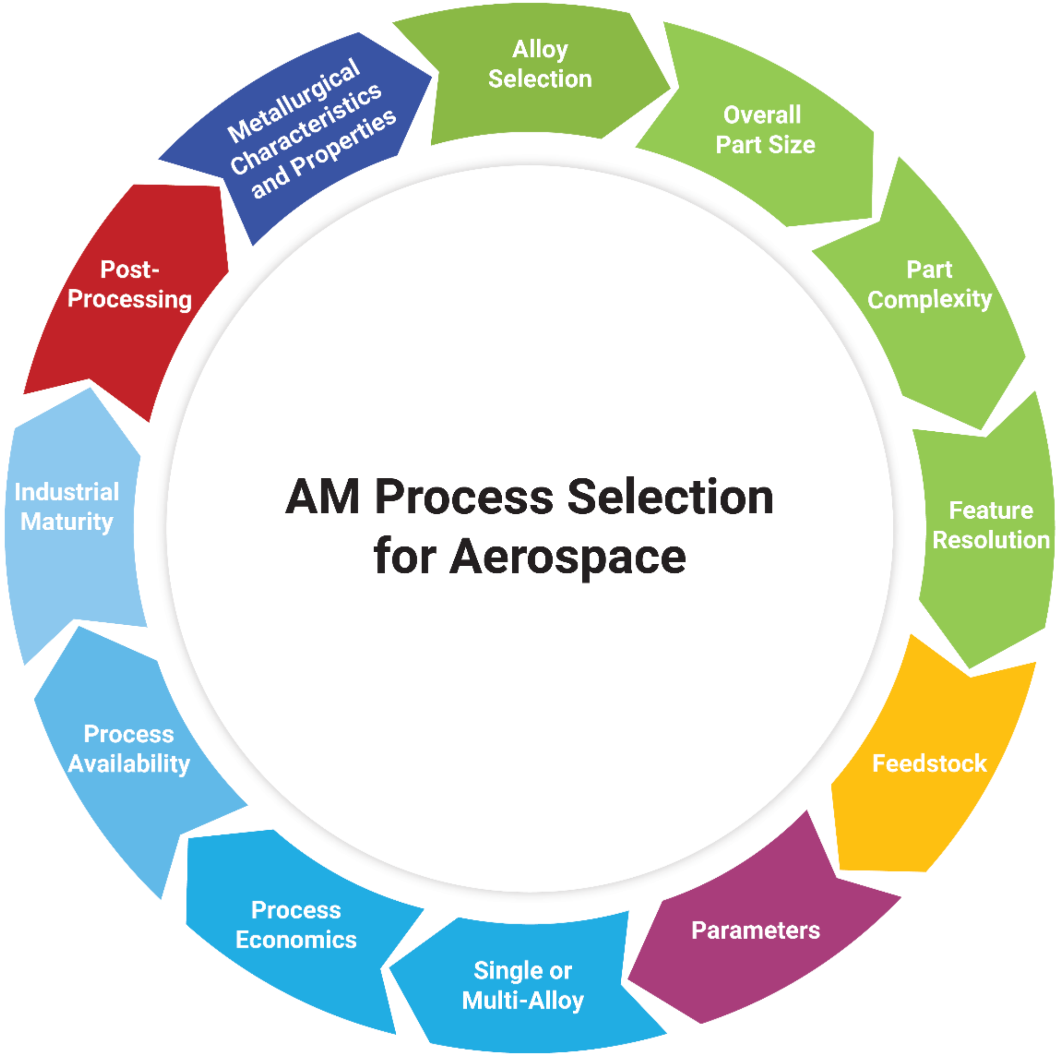
Directed Energy Deposition



L-PBF of complex components, new alloy developments for harsh environment



Methodical AM Process Selection



- What is the **alloy** required for the application?
- What is the **overall part size**?
- What is the **feature resolution** and internal **complexities**?
- Is it a **single alloy or multiple**?
- What are **programmatic requirements** such as cost, schedule, risk tolerance?
- What are the end-use environments and **properties required**?
- What is the **qualification/certification** path for the application/process?

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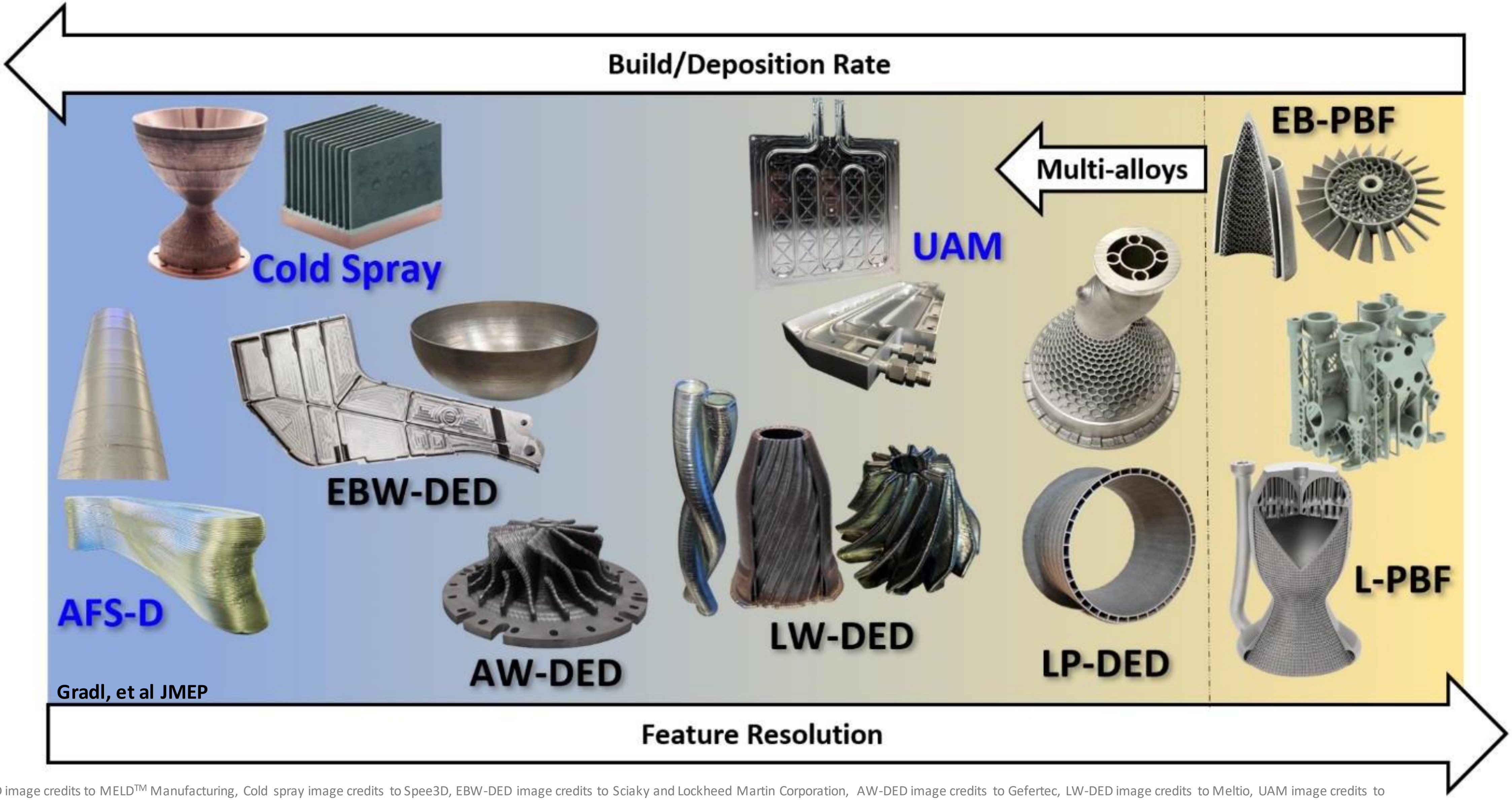
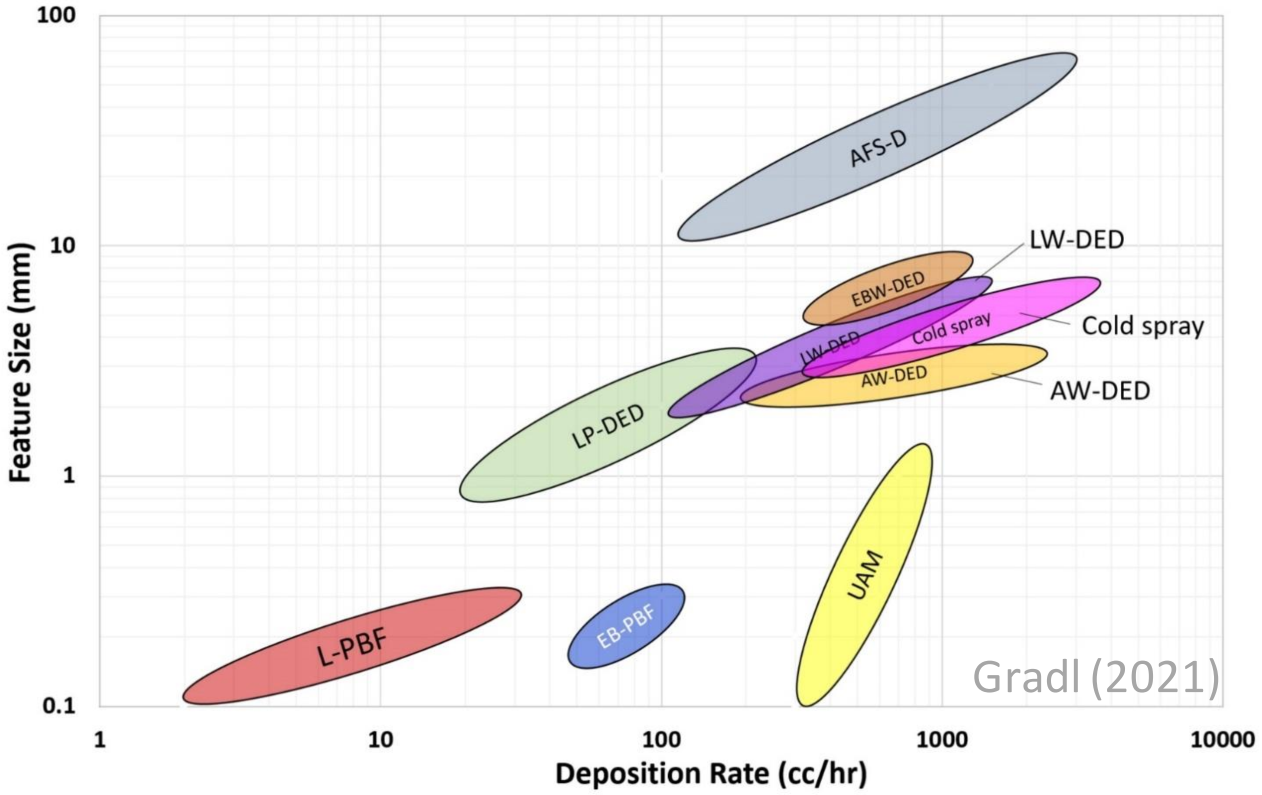
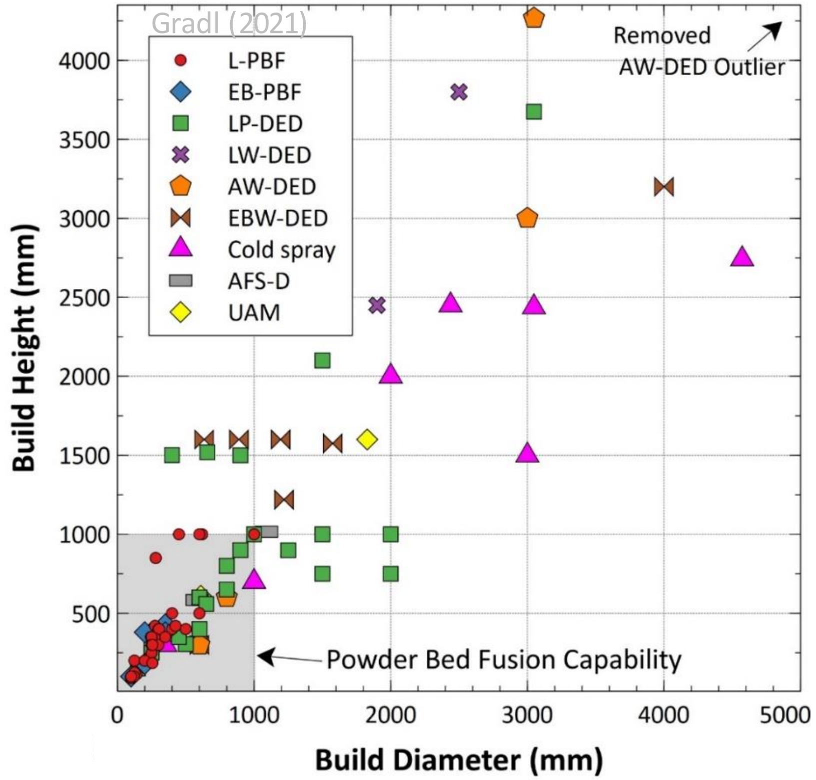
Criteria and Comparison Various Metal AM Processes



CREDITS: AFS-D image credits to MELD[TM] Manufacturing, Cold spray image credits to Spee3D, EBW-DED image credits to Sciaky and Lockheed Martin Corporation, AW-DED image credits to Gefertec, LW-DED image credits to Meltio, UAM image credits to Fabrisonic and NASA JPL, LP-DED image credits to DEPOZ project led by IRT Saint-Exupery and Formalloy, L-PBF image credits to Renishaw plc and CellCore GmbH/Sol Solutions Group AG, EB-PBF image credits to Wayland and GE Additive/Arcam.

Various criteria for selecting AM techniques





- Complexity of Features
- Scale of Hardware
- Material Physics
- Cost
- Material Efficiency
- Speed of Process
- Material Properties
- Internal Geometry
- Availability
- Post Processing

References:

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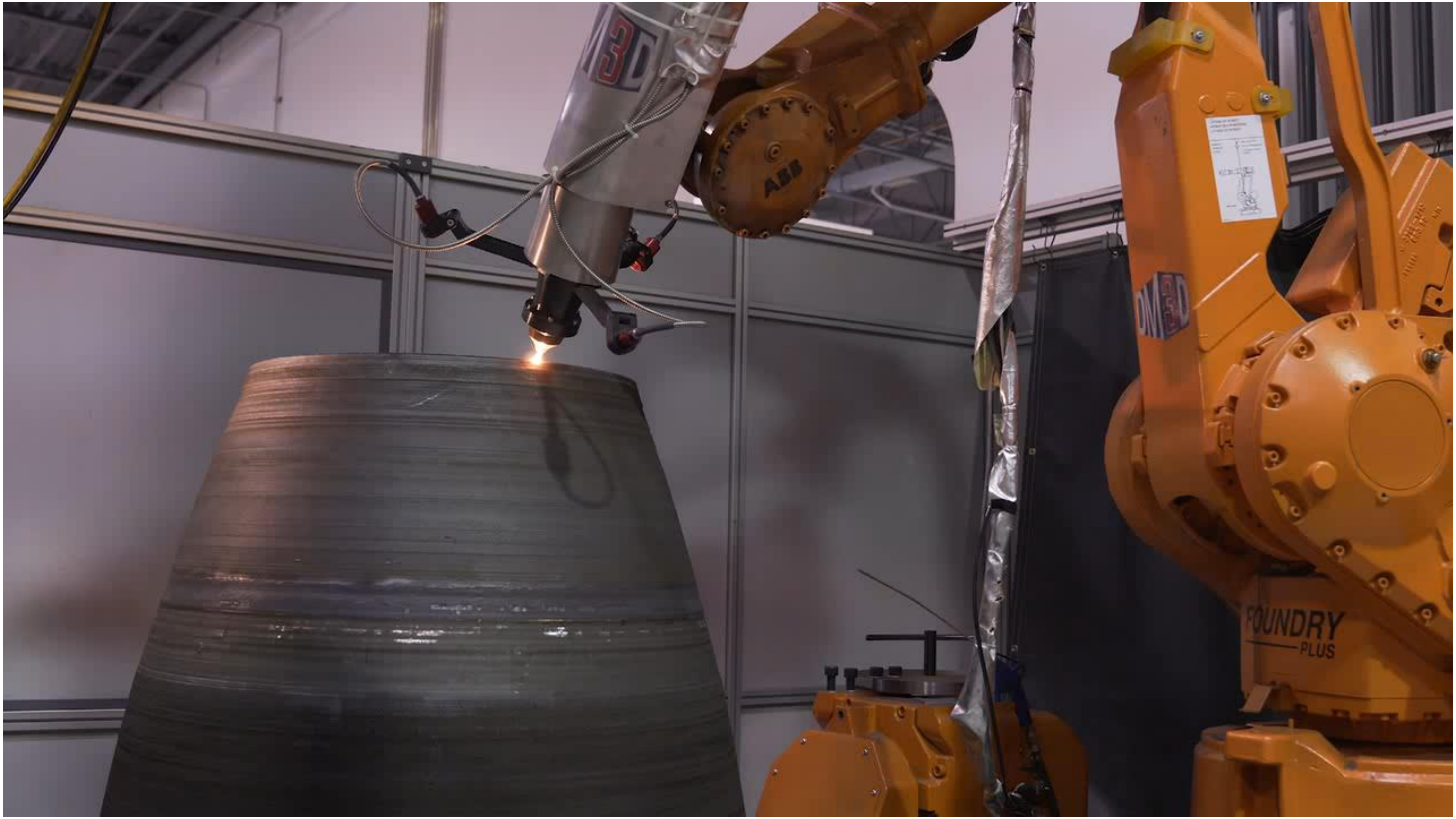
- AIAA Book: Metal Additive Manufacturing for Propulsion Systems, Gradl, Protz, Mireles, Garcia (unreleased)

Laser Powder Directed Energy Deposition (DED)



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

60” (1.52 m) diameter and 70” (1.78 m) height with integral channels

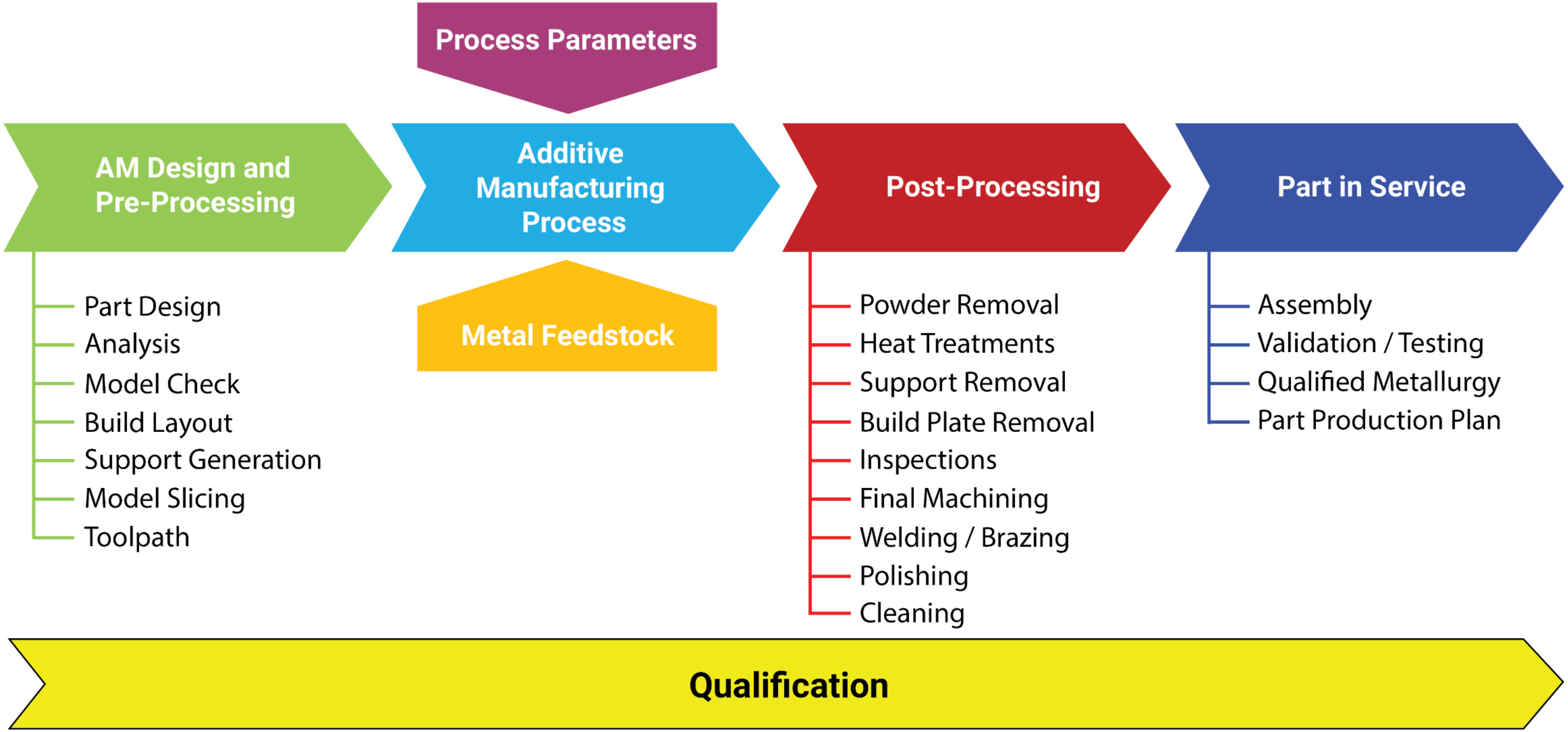
90 day deposition

95” (2.41 m) dia and 111” (2.82 m) height

Near Net Shape Forging Replacement

Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

Additive Manufacturing Typical Process Flow

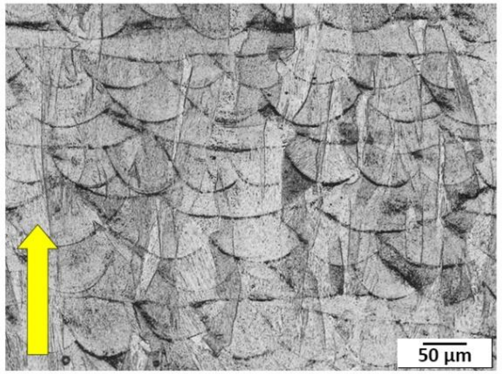


Proper AM process selection requires an integrated evaluation of all process lifecycle steps

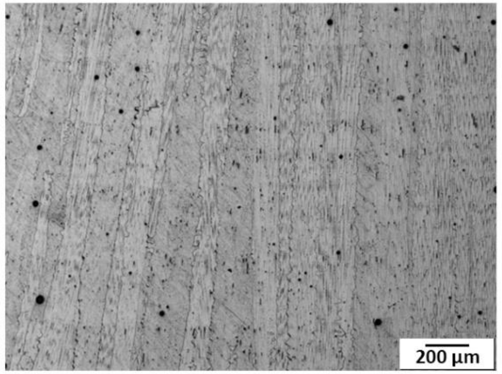
Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.

Microstructure of Various AM Processes
Inconel 625

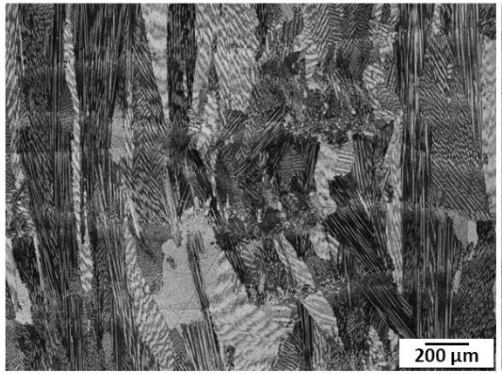
As-built microstructure of Inconel 625 => Requires proper post-processing heat treatments



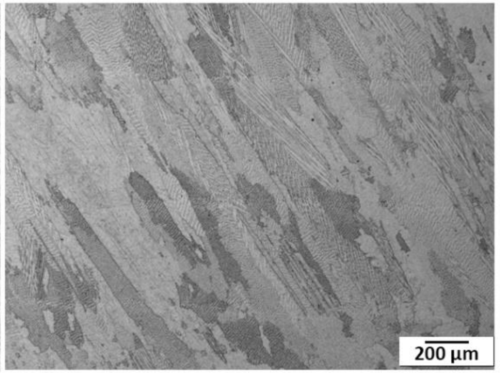
A) Laser Powder Bed Fusion



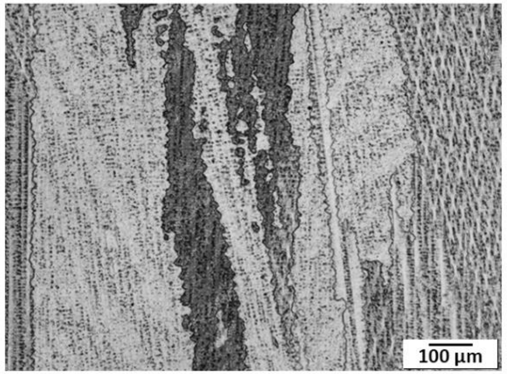
B) Electron Beam Powder Bed Fusion



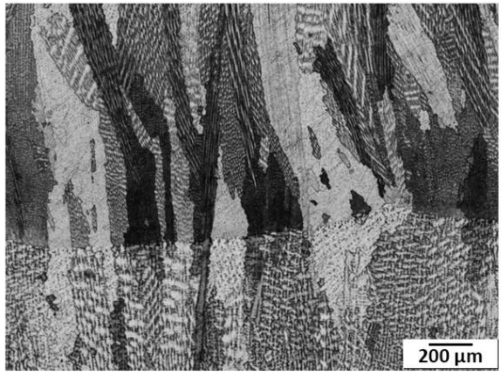
C) Laser Powder DED (1070 W)



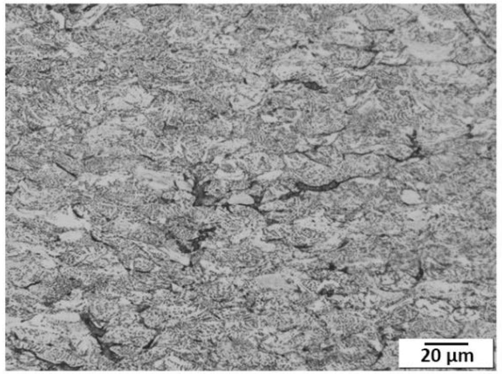
D) Laser Wire DED



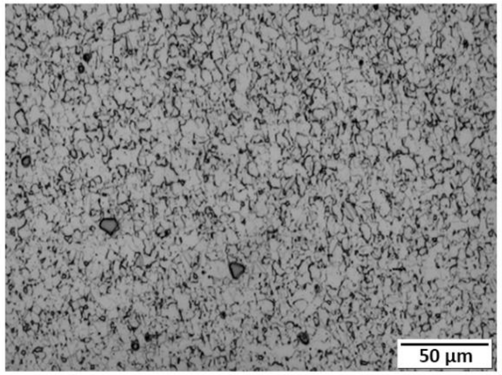
E) Arc Wire DED



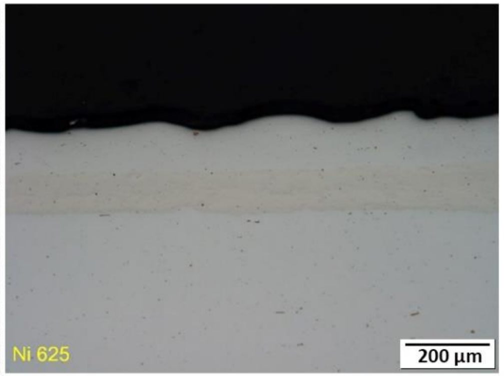
F) Electron Beam Wire DED



G) Cold Spray



H) Additive Friction Stir Deposition



I) Ultrasonic Additive Manufacturing

Each AM process results in different grain structures, which ultimately influence properties

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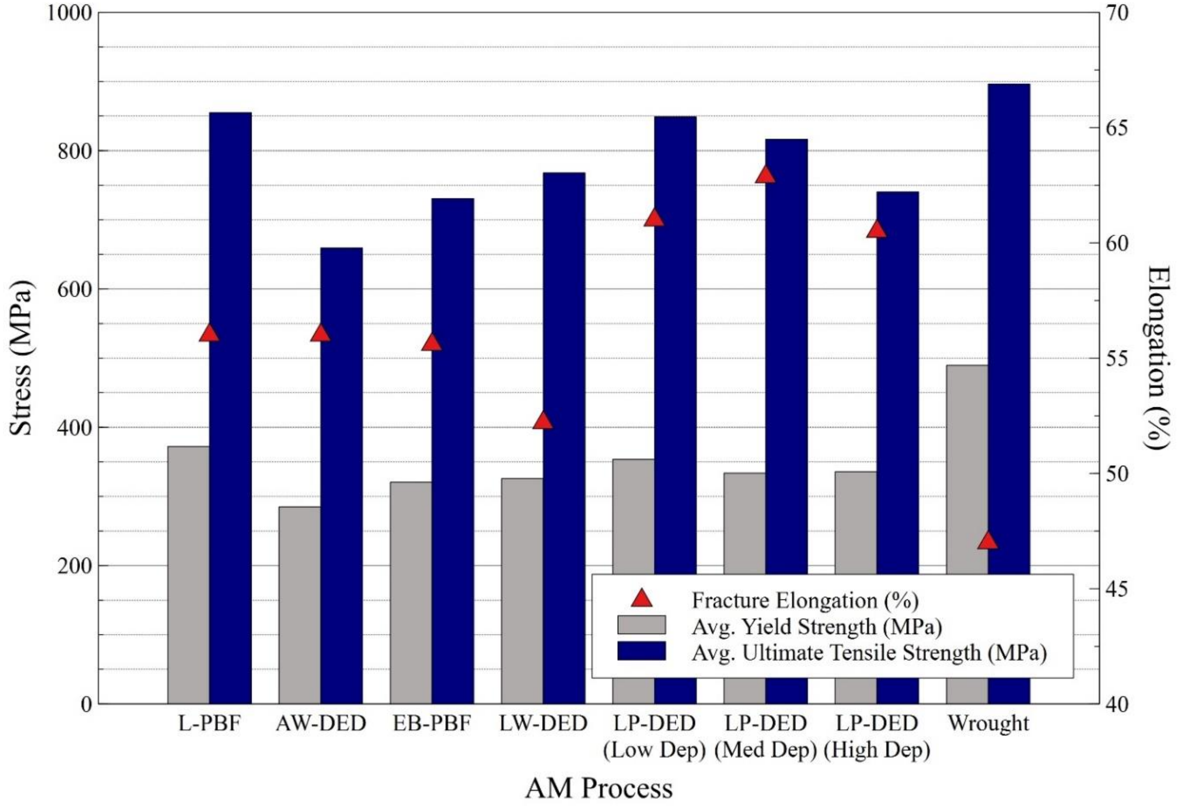
- Image from Mark Norfolk, Fabrisonic

Material Properties for Various AM Processes

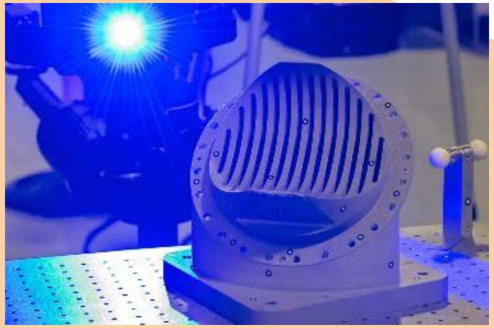
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Cold spray….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build.
- Each AM process results in different grain distributions, precipitates, and porosity, all of which influence final properties.
- Heat treatments should be developed based on the requirements and environment of the end component use.
- Properties should be developed after AM process is stable and parameters confirmed.

Room Temperature UTS



*Not design data and provided as an example only

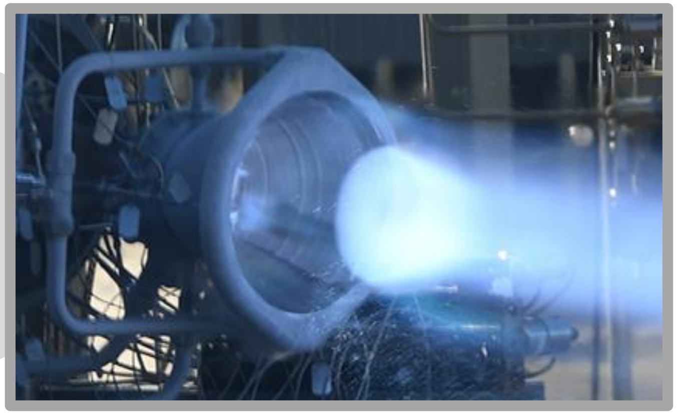
Industrial Maturity and TRL of AM Processes

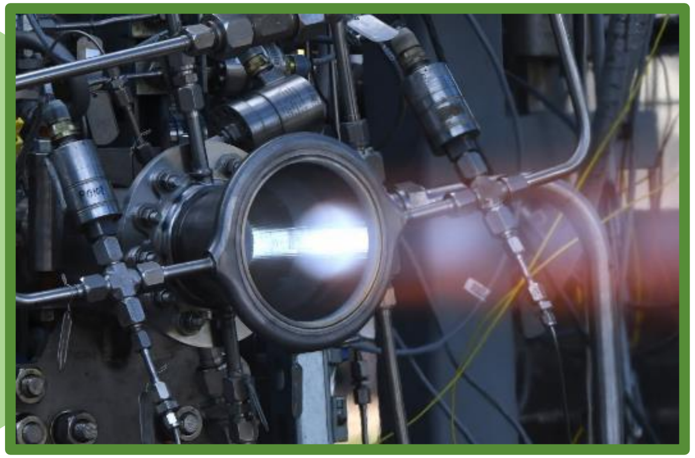


L-PBF

Cold spray

LP-DED





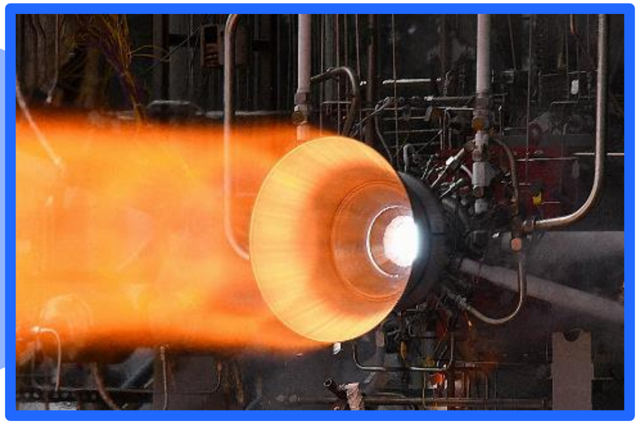
L-PBF

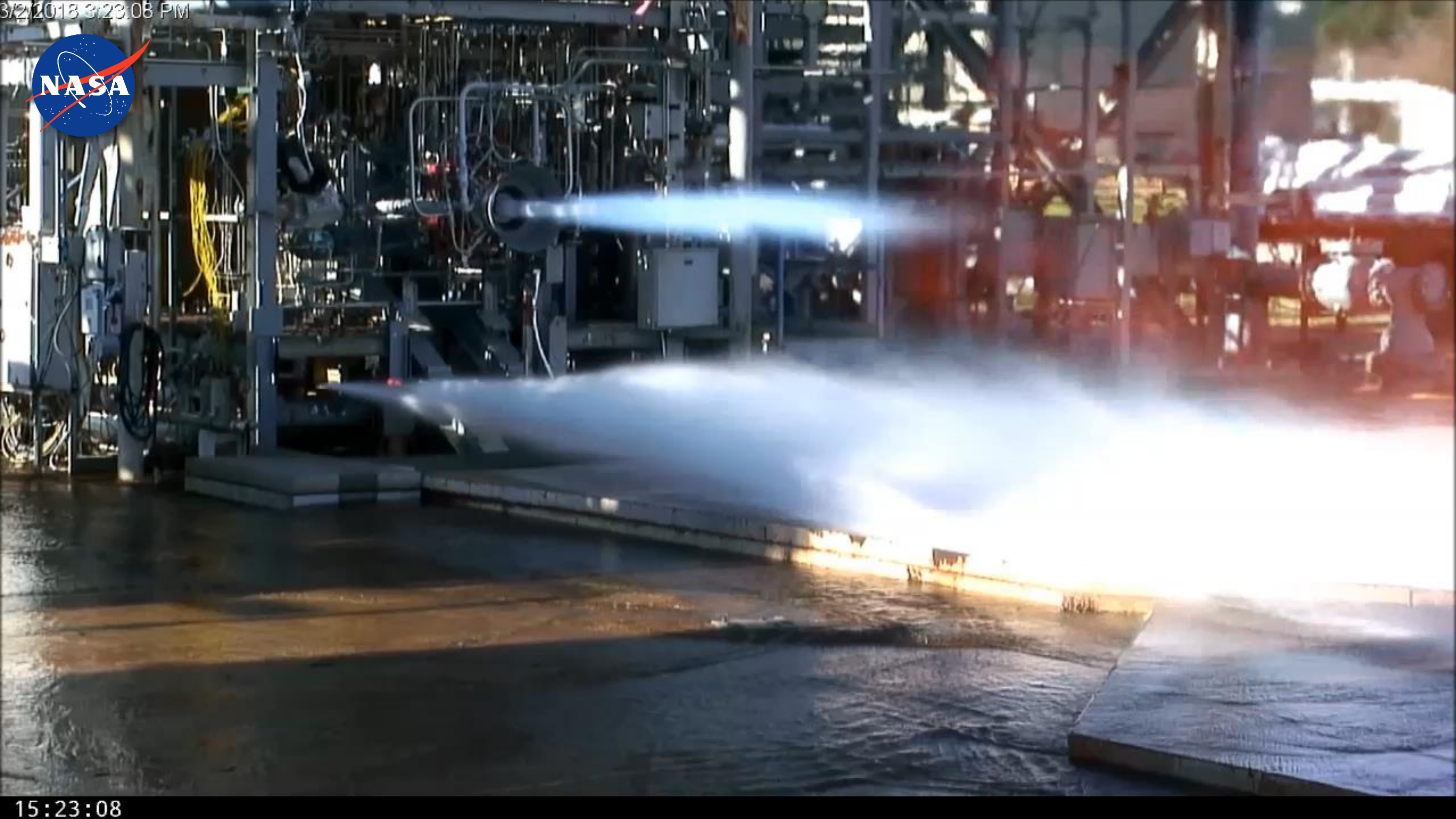
AW-DED

LW-DED

L-PBF

EBW-DED

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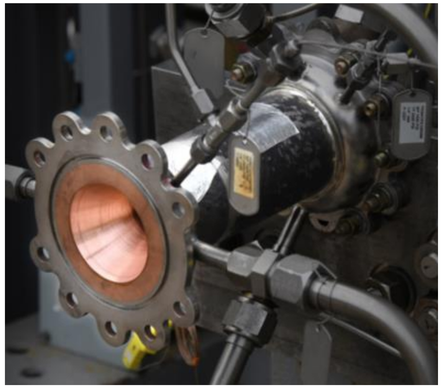
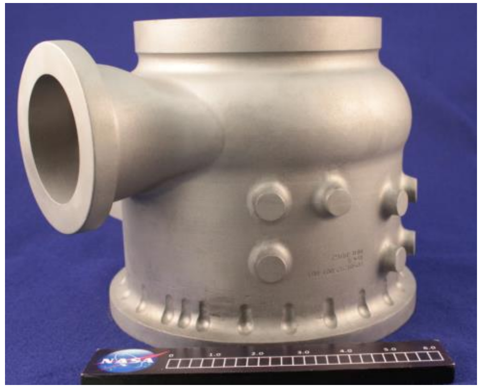
General Summary

- Various AM processes exist each with unique advantages and disadvantages.
- It's *all* welding, so same physics apply.
- Additive manufacturing is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense.
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM.
- Additive manufacturing takes practice!
- Standards and certification of the AM processes are in-work.
- AM is evolving and there is a lot of work ahead.





<u>Contact:</u>

Paul Gradl

NASA MSFC

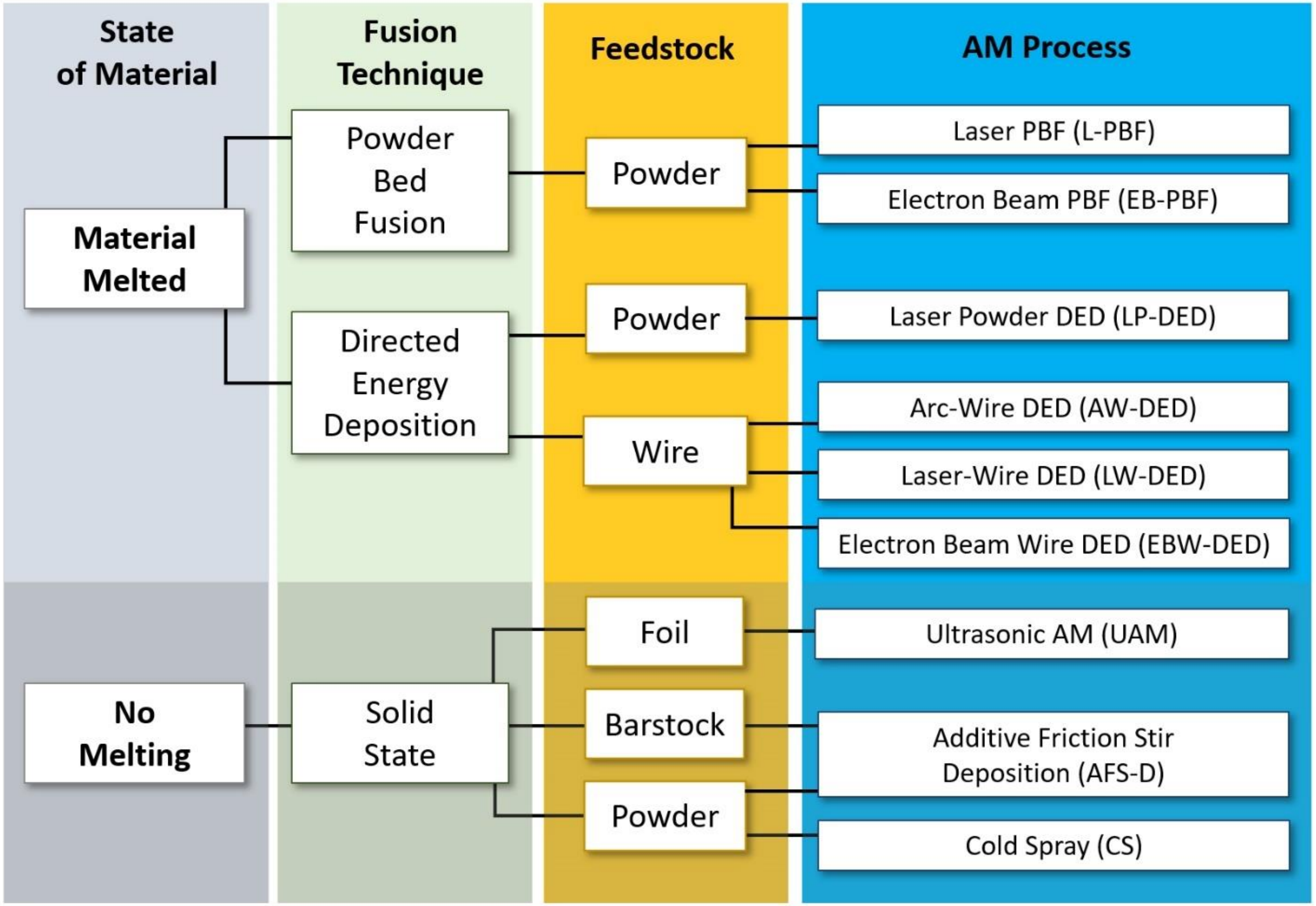
256.544.2455

Paul.R.Gradl@nasa.gov

Emerging Areas of Development

- Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.
- Ongoing development for large scale AM using DED and other processes.
- Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters.
- Polishing (surface enhancements internally) and post-processing development.
- Combining various AM processes for multi-alloy solutions or additional design options.
- Advancement of commercial supply chain for unique alloys (GRCop-42, NASA HR-1, JBK-75).
- New alloy development (Refractory, Ox-rich environments, AM-specific alloys).
- Material databases of metal AM properties to allow for conceptual design – tensile, fatigue, and thermophysical.
- Design complexity using lattices, topology optimization, generative design, and thin-wall structures.
- Standards and certification of metal AM are evolving for human spaceflight.

Various Metal AM Processes



Many AM processes exists and must be traded (along with traditional techniques) to optimize

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